THEORY AND USE
of Architectural Acoustical Materials

ACOUSTICAL MATERIALS ASSOCIATION

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THEORY AND USE OF ACOUSTICAL MATERIALS

Paul E. Sabine, Ph. D.

THE control of sound in building has come in recent years to be a problem with which architects and engineers have increasingly to deal. Generally, the science of acoustics has not hitherto been a part of the technical training for these professions. As a result, many men who have the job of designing and constructing buildings find themselves confronted with problems in a field of physical science with which they have barely more than a speaking acquaintance. Moreover, the very rapid advance made in recent years in our knowledge of the quantitative aspects of sound in its relation to buildings and building construction has led to the development of a terminology which is quite unintelligible to any but the expert in acoustics. The material presented herein is intended to serve as a basis for an intelligent appreciation of the problem of sound control in buildings, to explain the meaning of the terms used in the discussion of these problems, and to indicate the practical methods that have been found for their solution.

Section 1

MEANING AND USE OF ACOUSTICAL TERMS

1 FREQUENCY, VELOCITY AND WAVE LENGTH

Sound may be defined in two ways—either as the sensation produced by stimulation of the auditory nerve or as the physical cause of that stimulation. We shall be more concerned with sound in the latter sense, confining our use of the term to sound in air and to such sounds as produce the sensation of hearing.

A vibrating body will impart a portion of its energy to the air surrounding it, i. e. it will generate SOUND WAVES. The frequency of vibration—the number of complete round trip excursions per second—is expressed as so many CYCLES PER SECOND (c. p. s.), or more briefly CYCLES. Consider one to and fro movement of the surface of a vibrating body. Its forward motion compresses the layer of air adjacent to it, causing an increase of the pressure above the normal atmospheric pressure. The return movement will cause a decrease of pressure below the normal. This fluctuation of the air pressure above and below the normal will be transmitted with a definite velocity to successive layers. The transfer of energy through the air by successive pressure variations in it is called a SOUND WAVE. The frequency with which the pressure changes occur at any point in the path of the wave is the same as that of the vibrating body which generates the wave and is spoken of as the FREQUENCY OF SOUND. Experiment shows that the velocity of sound of all frequencies is approximately 1120 feet per second or 763 miles per hour. It varies slightly with temperature increasing about 1.1 ft. per second for 1 degree Fahrenheit from 1099 ft. per second at 32° F. to 1130 ft per second at 70° F.

The distance which sound of a given frequency travels during the time of a single vibration is called the WAVE LENGTH. If, for example, the source of sound makes 200 vibrations per second and the wave travels 1120 feet in that time, then the distance travelled in the time of one vibration is 1/200 of 1100 feet or 5.6 feet. Generalizing, we have

$$\text{Velocity} = \text{Wave length} \times \text{frequency}$$

or

$$\text{Wave length} = \frac{\text{Velocity}}{\text{Frequency}}$$

2 FREQUENCY AND PITCH

The difference in the sensation produced by a change in the frequency of vibration of the sound source is spoken of as a DIFFERENCE IN PITCH. Frequency is expressed in cycles per second. Pitch is expressed in tones of the musical scale. Doubling the frequency of vibration raises the pitch by one octave. Thus, the frequency of the A above middle C on a piano tuned to concert pitch is, by definition, 440 c. p. s. The A in the next higher octave is 880 c. p. s., and in the octave below 220 c. p. s. The range of frequencies that will produce audible sound is ordinarily given as 20 to 20,000 c. p. s. corresponding to a range in pitch of slightly less than 10 octaves. The frequency range and the range of wave lengths in air, assuming a velocity of 1120 ft. per second, for the tones of various musical instruments is shown in Table I.

Table 1

INSTRUMENT	FREQUENCY RANGE (c. p. s.)	RANGE OF WAVE LENGTH (ft.)
Piano	27 — 4186	41.5 — 0.27
Bass Viol	41 — 246	27.4 — 4.55
Cello	65 — 659	17.2 — 1.70
Violin	196 — 2093	5.7 — 0.54
Flute	261 — 2093	4.3 — 0.54
Oboe	233 — 1568	4.8 — 0.72
B♭ Clarinet	73 — 698	15.4 — 1.61
Singing Voice—		
Male	82 — 466	13.7 — 2.40
Female	196 — 1046	5.7 — 1.07

3 MUSICAL SOUNDS AND NOISE

It is not easy to draw a sharp line of distinction between a musical sound and a noise. To her doting mama, the sound of Arabella's voice practicing scales is musical. To the long suffering neighbors, it rates as noise. Psychologically defined, a musical sound is pleasing. A noise is not. Physically, a musical sound consists of a single definite frequency or a combination of simply and definitely related frequencies. Sound of a single frequency is spoken of as a pure or SIMPLE TONE and is produced by a body vibrating in a single mode. The sound of a tuning fork is a common example. A string of the piano or violin vibrates as a whole and at the same time in segments producing a COMPLEX MUSICAL TONE. The simple components of a complex tone have frequencies which are exact multiples of the LOWEST or FUNDAMENTAL frequency.

The higher frequency components are called HARMONICS when they are exact multiples of the fundamental frequency or more generally OVERTONES. The distribution and relative intensity of the overtones of a musical sound determines the QUALITY or TIMBRE of the sound. The difference which the ear recognizes between the tones of the same pitch and loudness from different musical instruments is a difference in QUALITY. The frequencies given in Table I are those of the fundamental components of the tones produced by instruments listed. Ordinarily it is the fundamental frequency which determines the pitch of a complex musical tone.

Physically, a noise differs from a musical sound in not having a definite frequency, or a series of simply related frequencies. A noise may produce a pitch sensation depending upon the particular part of the frequency range in which the vibrational energy is concentrated. A frequency analysis of the roar of a train crossing a trestle would show a peak of energy in the low frequency region. The screech of automobile brakes

is in the high portion of the frequency spectrum. Complete knowledge of the nature of a particular noise involves an analysis that determines the distribution of the total acoustic energy over the range of audible frequencies.

4 SPEECH

Acoustically, speech consists of a succession of mixed musical sounds and noises. VOWEL sounds are essentially musical sounds. Each vowel has a characteristic set of overtones given by the shape of the mouth cavities in producing it. The overtones that distinguish the various vowels lie in the frequency range from 200 to 3000 c. p. s. Consonant sounds are characteristic noises produced by the positioning and movements of the lips and tongue in speaking. The fundamental tone of the speaking voice is determined by the rate of vibration of the vocal chords and normally has a frequency in the neighborhood of 125 c. p. s. for men's and 250 c. p. s. for women's voices.

5 PRESSURE VARIATIONS IN A SOUND WAVE

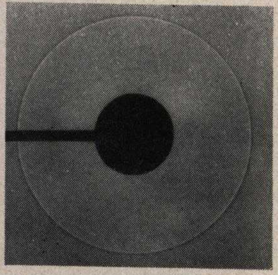

Fig. 1

Figure I is an instantaneous photograph of the pressure pulse in the air produced by the sharp snap of a heavy electric discharge between two electrodes shown as the dark disc at the center of the picture. The sudden expansion of the air due to the heat generated by the discharge produced a single pulse of condensation followed by a resultant rarefaction. If it were possible to produce a continuous sound intense enough to produce pressure changes that could be photographed, then a series of condensations and rarefactions as suggested by Figure 2 would be shown.

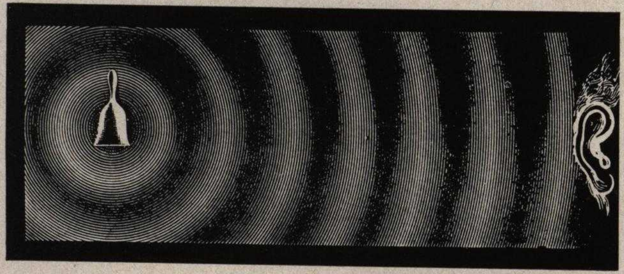

Fig. 2

A cathode ray oscilloscope is a device by which rapidly varying voltages or currents in an electric circuit may be shown graphically on a fluorescent screen. There are now certain types of microphones or transmitters built so that the instantaneous voltage generated by the movement of the diaphragm is proportional to the unbalanced pressure exerted on it. If the electrical output of such a microphone sufficiently amplified is fed into an oscilloscope, the variation with time of the pressure on the microphone diaphragm is shown by a trace on the screen of the oscilloscope.

Horizontal distances on the screen correspond to time differences, while vertical distances are proportional to the instantaneous values of the pressure. The period of the horizontal sweep can be adjusted to coincide with the period of a single pressure cycle or a small multiple thereof, so that the trace on the screen is a plot of the pressure variation at the face of the diaphragm over one cycle or a small number of cycles. Such a trace is spoken of as a WAVE FORM of the sound pressure.

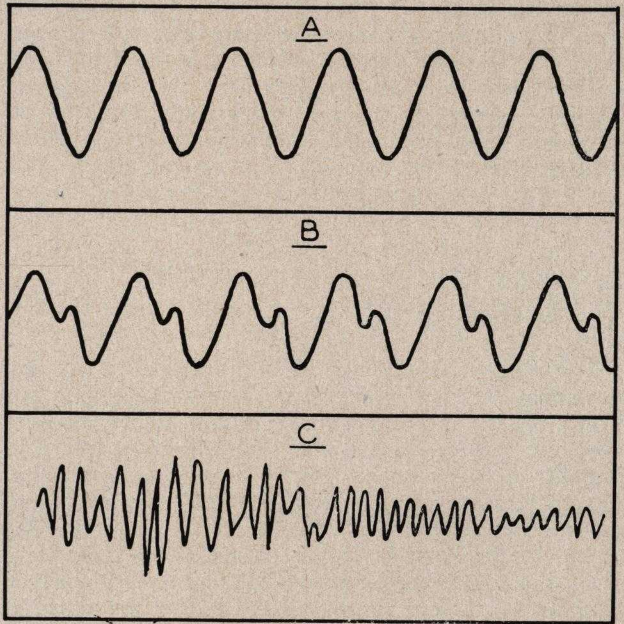

Fig. 3

In Figure 3 are shown the wave forms of a simple or pure tone—a so-called SIMPLE HARMONIC VIBRATION, a complex tone and a noise. The first two are periodic, the form repeating itself at regular intervals, whereas the wave form of the noise is quite nondescript.

6 SOUND PRESSURE AND INTENSITY OF SOUND

Every boy who has ever used a hand pump on a bicycle tire knows that it takes WORK to move the pump piston against the air pressure in the tire. ENERGY is the capacity to do work. POWER is the RATE of DOING WORK, i. e. the rate at which energy is transferred from one body to another. If the boy who pumps up the bicycle tire happens also to play tuba in the High School band, he can testify that it takes work to set up the alternating pressures in the horn, the energy of which is transmitted as sound waves in the air. In the process, each layer of air in a progressive wave transmits energy to the succeeding layer. The INTENSITY of a sound, independently of its frequency, is proportional to the average of the square of the pressure taken over a complete pressure cycle. Intensity is defined as the power in watts that is transmitted across one square centimeter of the wave front perpendicular to the direction in which the sound is travelling.

The power of even the most intense sound expressed in watts is extremely small. The unit of acoustical intensity is 10^{-16} watts per square centimeter. (10^{-16} is the physicist's way of writing the fraction 1 over 10 followed by 15 ciphers.) There should be a name for this unit, but there isn't. This intensity is slightly less than the least intensity of a 1000 cycle tone which is audible to the human ear. Even a painfully intense sound has an intensity of only 1/1000 of a watt per square centimeter. The square root of the average square ("root-mean-square") of the sound pressure that corresponds to 10^{-16} watts per square centimeter is .0002 dynes per square centimeter. A dyne is a force equal to 1/980 of the weight of a gram so that a r.m.s. sound pressure of .0002 dynes per square centimeter is equal to about two millionths of a gram weight per square centimeter. Intensity of sound is usually expressed in 10^{-16} watt units, and sound pressure in .0002 dyne units per square centimeter.

7 INTENSITY, INTENSITY LEVEL, DECIBEL SCALE

The range of intensities in the sounds of every day experience is truly enormous. In terms of the unit just discussed, the intensity of the faintest sound which a normally acute ear can hear is slightly more than I. The intensity of the sound of the voice speaking in a confidential tone is of the order of 10,000, ordinary conversation is 100,000 to 1,000,000, street noise 10,000,000 to 1,000,000,000, and a painfully loud sound is from one to ten trillions of these units. As an acoustical device, the ear is unsurpassed in the vast range of intensities to which it will respond without being damaged, as well as in its extreme sensitivity to faint signals. It is, however, relatively insensitive to CHANGES of intensity. Roughly speaking, the intensity of sound has to be increased by about 26 per cent in order for the ear to register a change in the loudness sensation produced.

Because of the awkwardness of handling numbers of such magnitudes and because of the roughly logarithmic response of the ear, the practice has been adopted of expressing sound intensities on a logarithmic scale. A simple slide rule is a device for adding and subtracting the logarithms of numbers. The linear distance on the scale is proportional to the logarithm of the ratio of the number markings on the scale at the two ends of the distance. In Fig. 4, the spacings between the integral ratios shown on the bottom scale are proportional to the differences between the logarithms of these ratios as shown on the linear scale directly above it. Thus the logarithm of the ratio 2:1 is a trifle more than 0.3, of 4:1 is a trifle more than 0.6, and of 8:1 somewhat more than 0.9. The logarithm of a 10 to 1 ratio is 1.0. Thus, multiplying a number by 2 increases its logarithm by 0.3, by 4 increases its logarithm by 0.6, and by 10 increases its logarithm by 1.0. The graduations on the top scale are indicated as 10 times the logarithms of the ratios of the bottom scale. The upper scale may be called a DECIBEL LEVEL SCALE, and is the scale which is used in acoustical jargon to indicate the relative intensities of different sounds. Thus if one sound has twice the intensity of another, it is said to be at a 3 decibel (db.) higher level. Increasing the intensity 10 fold raises the level 10 db., 100 fold 20 db., 1000 fold 30 db., and so on.

Figure 5 shows the relation between intensities and intensity levels in decibels in conventional graph form. The horizontal scale is logarithmic and corresponds to the scale on an ordinary slide rule. The ordinates of the points on the straight line graph are 10 times the logarithms of the numbers shown on the horizontal scale. In other words, the INTENSITY LEVEL in decibels is plotted against the intensity. The first vertical scale corresponds to the levels of intensities from 1 to 10, the second from 10 to 100, and the third from 100 to 1000, and so on. The graph can be extended to give the intensity level of any intensity by remembering that multiplying the intensity by 10 raises the intensity level by 10 db. Thus the intensity level for 2.5 is 4 decibels, 25 is 14 db., 250, 24 db., 2,500,000, 64 db.

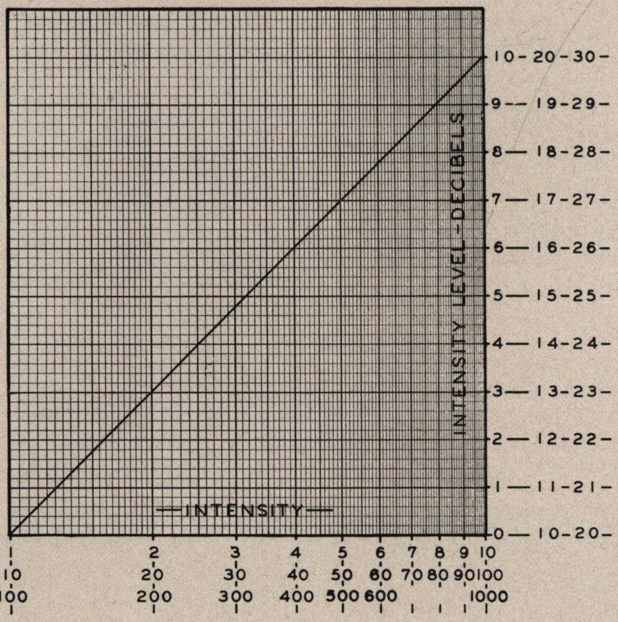

Fig. 5

8 SOUND LEVEL METER

A sound level meter is a device for measuring the sound intensity level of sound. It consists essentially of a microphone or transmitter, whose vibration under the action of the alternating pressure of the sound generates

10 LOG RATIO DB.	0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0 1.0
LOG RATIO	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9 1.0

RATIO	1:1	2:1	3:1	4:1	5:1	6:1	7:1	8:1	10:1 9:1

Fig. 4

minute electrical voltages in the microphone circuit, a vacuum tube amplifier, an electrical network designed to make the frequency response conform to the frequency response of the ear, a variable attenuator and a meter calibrated to read the intensity level of the

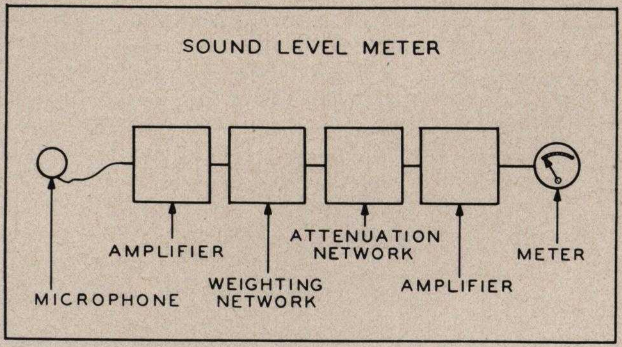

Fig. 6

Fig. 7

sound in decibels above the reference level of 10^{-16} watts per square centimeter. The components of such an instrument are shown schematically in Figure 6 and a widely used instrument of this type is shown in Figure 7.

An idea of the meaning of sound intensity levels expressed in decibels can be gained from Figure 8. Remembering that a 10-db. INCREASE in intensity level corresponds to a 10-fold increase in intensity, it is apparent that the intensity of a sound that begins to be painfully loud is one trillion times the minimum audible intensity.

9 LOUDNESS AND INTENSITY

The loudness of sound (sensation) depends upon the intensity, but it also depends upon the frequency of the sound and the characteristics of the human ear. The intensity of sound is a purely physical quantity, whereas, the loudness depends also upon the characteristics of the ear. Thus, the intensity of a given sound striking the ear of a normal hearing person and of a hard-of-hearing person might be the same, but the loudness sensation would be quite different. Again, a 100 cycle tone that is barely audible has about 5000 times the intensity of a 1000 cycle tone that is equally loud, i. e. barely audible, whereas 100 cycle and 1000 cycle tones would sound equally loud at a 100 db. level. The relationship between frequency intensity and loudness is quite involved. We do have, however, a sense of RELATIVE LOUDNESS so that there is a fair measure of agreement among trained observers in their judgments as to when one sound is one-half, one-third and so on as loud as another. The question is often asked, "Suppose we reduce the intensity level of a noise by 10 decibels, what percentage reduction in LOUDNESS have we obtained?" The answer is that it depends on what the initial level was. The chart of Figure 9 can be used to give an approximate answer for different values of the original level. From the chart we obtain the values as shown in Table 2 for the per cent loudness reduction for different initial levels and 6 and 10 db. reduction in loudness level:

Speaking generally, one may say that the quantitative evaluation of the magnitude of sensations is a psychological rather than a physical problem, so that the acoustical engineer prefers to deal with those aspects of sound that are subject to physical measurements. The foregoing is presented simply for the benefit of those who INSIST on expressing things on a percentage basis.

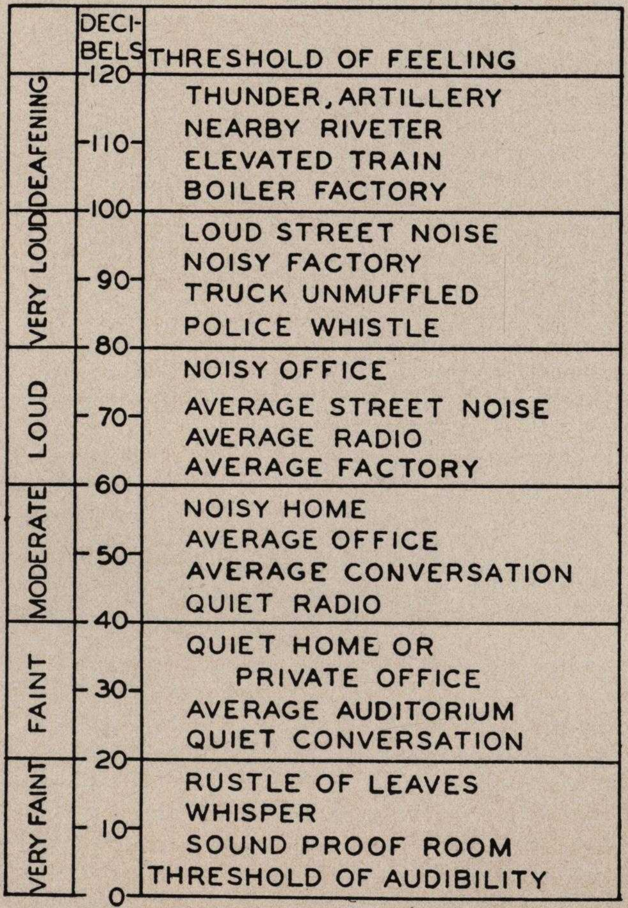

Fig. 8

For intensities and frequencies of sound ordinarily encountered, a difference of at least 1 decibel in the intensity level is required to produce a perceptible difference in loudness under the most favorable listening conditions. If this relation were exact and held over the entire range of audible intensities, there would be 120 to 130 degrees of perceptible loudness difference between the least audible sound and a painfully loud sound.

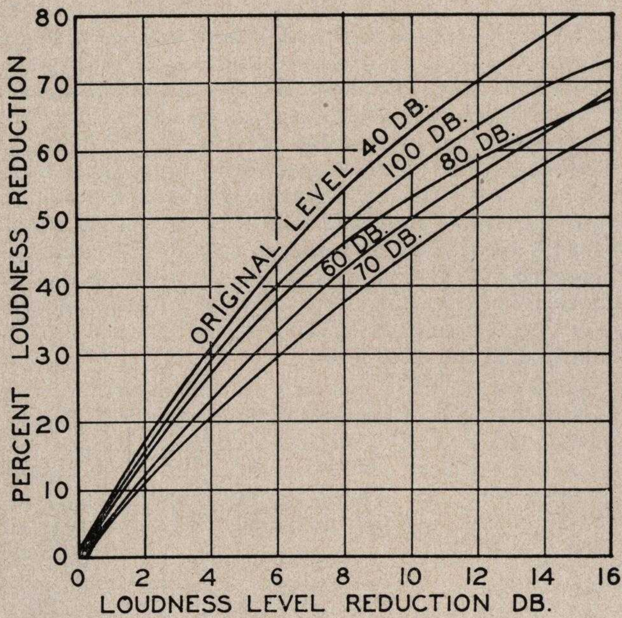

Fig. 9

Table 2

ORIGINAL LOUDNESS LEVEL (DB)	REDUCTION IN DECIBELS	PER CENT LOUDNESS REDUCTION
40	10 6	62 43
60	10 6	50 33
70	10 6	44 29
80	10 6	53 38
100	10 6	56 40

REFLECTION AND ABSORPTION OF SOUND

Whenever sound strikes a solid barrier a part of its energy is reflected, part is absorbed and part is transmitted to the space beyond. If the sound originates inside a room, the portions absorbed and transmitted by the walls are not returned so we may take the two together under the single heading absorption. We call the fraction that is returned to the room, the REFLECTION COEFFICIENT. The fraction not returned is the ABSORPTION COEFFICIENT.

In Figure 10, a sound pulse incident upon a hard highly REFLECTING surface is shown at (a). A similar pulse striking a highly absorbing surface is shown at (b). On the photographic evidence, the latter would indicate an absorption coefficient of 1.00, or complete absorption, but as a matter of fact all that can be inferred is that the intensity of the reflected portion is too small to be recorded on the photographic plate. It is extremely difficult in practice to secure PERFECT absorption for sounds of all frequencies.

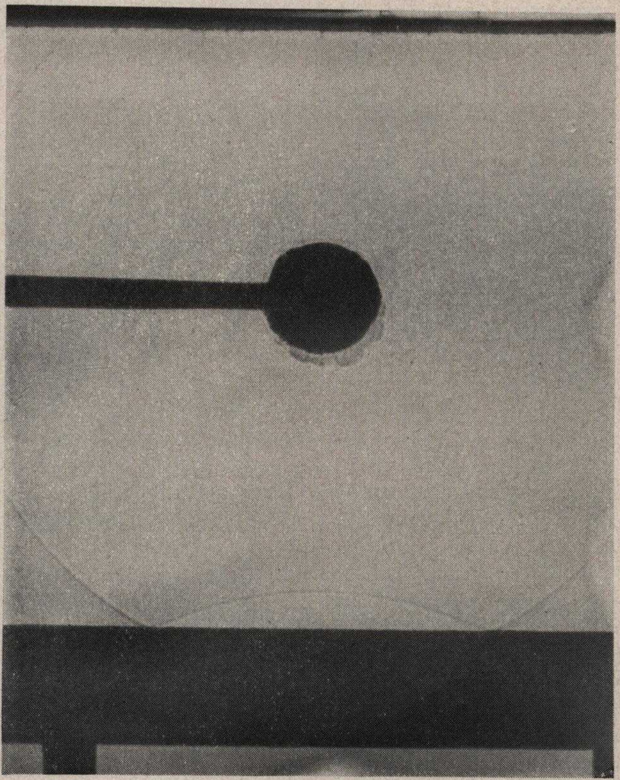

Fig. 10A

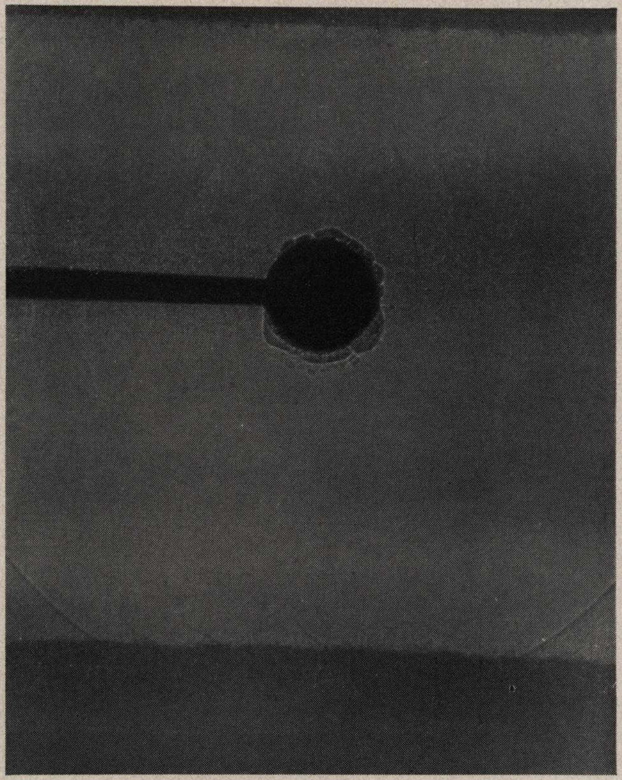

Fig. 10B

1 SOUND ABSORBENT MATERIALS

Absorption of sound involves the dissipation in the form of heat of the vibrational energy of sound waves. Speaking generally, materials that are absorbent in any considerable degree are either POROUS, inelastically FLEXIBLE or inelastically COMPRESSIBLE, or they may possess two or more of these properties in varying degrees. In porous absorbent materials the pores are inter-communicating and penetrate the surface. The alternating pressure in the sound wave forces the air particles into the narrow channels of the pore structure where their vibrational energy is dissipated by the viscosity of the air and friction against the walls of the channels. Sealing the surface of such a material may decrease in considerable degree its sound absorbing efficiency. Felts, fabrics and fibrous materials of vegetable and mineral fibre absorb sound largely by virtue of their porosity and to a certain extent because of their inelastic flexibility and compressibility. Hard, non-yielding absorbents owe their absorption properties entirely to their porosity. Fibrous wall boards with an impervious surface and plywood owe what absorbent properties they have to their forced, inelastic flexural vibration under the alternating pressure of the sound waves at their surface.

Various means have been found of increasing the absorption coefficients of commercial absorbents, as by slotting, perforating, fissuring, or otherwise providing small apertures into the body of the materials. The mechanics of this effect is not completely understood. Depth, diameter and distribution of the holes over the surface of the material have been found to have an important effect on the sound absorbing efficiency. An important property of absorbents of this type is that painting does not, to any measurable degree, decrease

their absorbing efficiency so long as the paint does not clog the holes.

It has also been found that covering the surface of a porous material with a thin perforated screen of metal or other hard material produces a negligible effect on its sound absorbing efficiency. The explanation lies in the fact that a thin membrane of this type in which the perforated area may be as small as 10 per cent of the total area transmits practically 100 per cent of the sound energy to the absorbent back of it. At high frequencies, say above 2000 c. p. s., the effect of the perforated screen is measurable.

2 ECHO, MULTIPLE ECHO, REVERBERATION

When an observer is so placed with reference to a sound reflecting surface that the reflected sound comes to him as a distinct repetition of the direct sound, the phenomenon is called an *echo*. The reflected sound will not be perceived as an echo unless the time interval between the arrival of the direct and reflected sound is at least 1/20 of a second, corresponding to a path difference of about 56 feet. For a path difference less than this, the reflected sound will not be perceived as a repetition of the direct sound, but may serve to reinforce it. This fact is of considerable importance in the design of auditoriums.

MULTIPLE ECHO results from successive reflections of sound from two or more surfaces that arrive at the ear of an observer with intervening time intervals long enough to produce a series of distinct repetitions of the original sound. Multiple echoes, sometimes called "flutter echoes" are apt to be observed between reflecting parallel walls of otherwise highly damped rooms.

REVERBERATION is the persistence of sound within an enclosed space after the source of sound has been cut off. We may consider reverberation either as a series of multiple echoes of decreasing intensity so closely spaced in time as to merge into a continuous sound, or as the gradual diminution of the vibrational energy of the whole body of air within the enclosure due to absorption at the boundaries and, in a very slight degree, to the dissipation of energy in the air itself. Reverberation theory as its applies to the acoustic properties of rooms neglects the latter factor and assumes that the decrease in intensity is due to surface absorption.

3 BUILDING UP AND DECAY OF SOUND IN ROOMS

Suppose a source of sound, a loud speaker for example, starts producing a steady tone within a room. Starting from the source, the wave train spreads in all directions. Striking the boundaries of the room, it is partially absorbed and partially reflected, not once but many times. The average intensity of sound in the room thus builds up to a steady state in which the rate of emission of sound energy at the source just equals the rate of absorption at the boundaries. In other words, time is required to set the whole body of air in the room into vibration. Suppose now the source is cut off. The sound in the room does not immediately cease, but gradually dies away, the average intensity at any instant decreasing at a rate which is proportional to the average intensity at that instant. This means that the logarithm of the average intensity is decreasing at a uniform rate, or, in other words, the drop in intensity level expressed in decibels is proportional to the time measured from the instant of cut off of the source. Figure 11 shows the idealized case of the building up

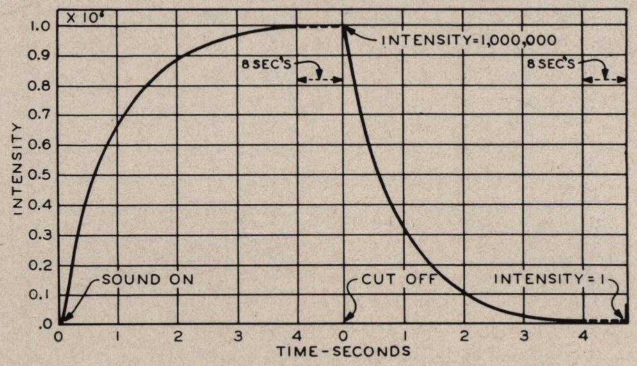

Fig. 11

and decay of sound from a steady source. Here the total time for the sound intensity to die away from an initial intensity of 1,000,000 to a final intensity of 1 is 12 seconds. A ratio of 1,000,000 to 1 in intensity corresponds to a drop of 60 dbs. in the intensity level. In

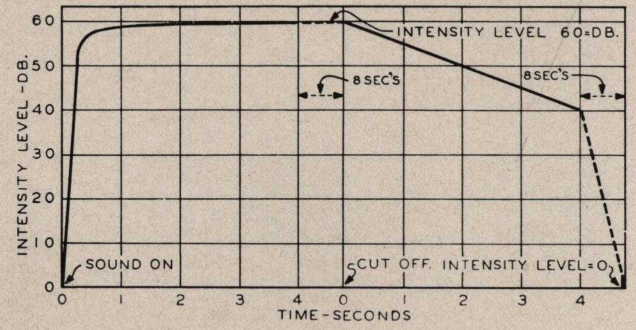

Fig. 12

Figure 12 intensity level is plotted against time and illustrates one advantage of the use of the decibel scale in dealing with acoustic phenomena.

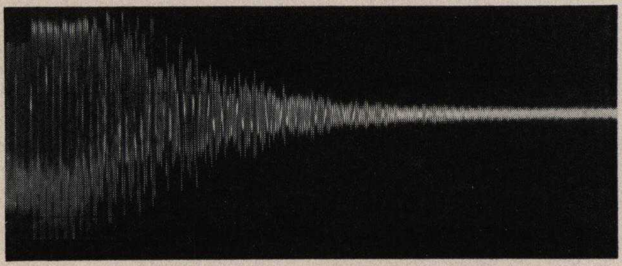

Fig. 13

As a matter of fact, the graphs of Figures 11 and 12 do not represent the phenomenon of reverberation within a room as it actually occurs. Figure 13 is an oscillograph record of the decay of the reverberation as recorded at a single position in the room. It will be noted that the decrease in amplitude with time follows

roughly the average curve of the right half of Figure 11, but with large fluctuation therefrom.

The smooth curve of Figures 11 and 12 represent the statistical average of records similar to that of Figure 13 taken in a large number of positions throughout the room and is a fairly factual representation of the way in which sound intensity builds up and dies away in rooms whose dimensions are large in comparison with the wave length of the sound the reverberation of which is being considered.

4 EFFECT OF REVERBERATION ON HEARING CONDITIONS

If one listens to a speaker close at hand speaking in a quiet tone of voice, the successive syllables arrive at the ear of the listener distinct and free from each other. The speech is easily intelligible. If, however, a speaker raises his voice in a large room, each syllable is prolonged running more or less into succeeding syllables with resultant confusion and loss of intelligibility. Similarly, the individual notes in music are prolonged by reverberation, and the effect is that of a piano played with the loud pedal held down continuously. The acoustic properties of rooms therefore depend in large measure, though not wholly, upon the reverberation times.

5 EFFECT OF VOLUME AND ABSORPTION ON REVERBERATION TIME

Reverberation Formula:

The REVERBERATION TIME of a room is defined as the time in seconds for the average intensity of the reverberant sound of a specified frequency to decrease to 1/1,000,000 of the initial intensity, or what is the same thing, for the intensity level to fall 60 db. The factors which affect the rate of decay and hence the Reverberation Time are (1) the volume of the room and (2) the sound absorbing properties of the bounding surfaces and of whatever objects are in the room.

The greater the volume the greater the average distance the sound will have to travel between reflections from the bounding surface and hence the greater the time required for a given decrease in intensity. Conversely, increasing the area of the surfaces at which reflection occurs and the absorption at these surfaces will increase the rate of decay of the reverberant sound. These two effects are summed up in the well known formula first given and experimentally proven by the pioneer work in this field of W. C. Sabine, namely:

$$T = \frac{.05V}{a}$$

T is the reverberation time as just defined for a 512 cycle tone, V is the total volume of the room in cubic feet, and *a* is the total equivalent absorption of the boundaries and of the contents of the room. The equivalent absorption* of a surface is expressed in SABINS, and is the product of the area of the surface and its sound absorption coefficient. Thus the absorption of 50 square feet of a material whose coefficient is 0.70 is

$$50 \times .70 = 35 \text{ sabins}$$

To compute *a* for any room the area of each surface is multiplied by its absorption coefficient, and the sum of these plus the absorption due to objects that may be in the room, seats, furnishings, and, in the case of audience rooms, people, gives us the total absorption, the *a* of the formula.

Other formulas applying with greater exactness to heavily damped rooms have been proposed and are in use, but most of the data available on desirable reverberation times are based on the simple formula given above. The interested reader is referred to the more recently published texts for detailed discussion.

6 DESIRABLE REVERBERATION TIMES

The Reverberation Time that is desirable for any particular room depends upon a number of considerations. Among them are volume, the usual audience, and the contemplated use, that is, whether the room is intended for music or speech, or both, with or without public address system, or for sound motion pictures and so forth. For this reason, no very precise values of the desirable reverberation time should be given. In rooms such as concert halls or operatic theaters, where good acoustic properties are of paramount importance, careful consideration should be given to all of these

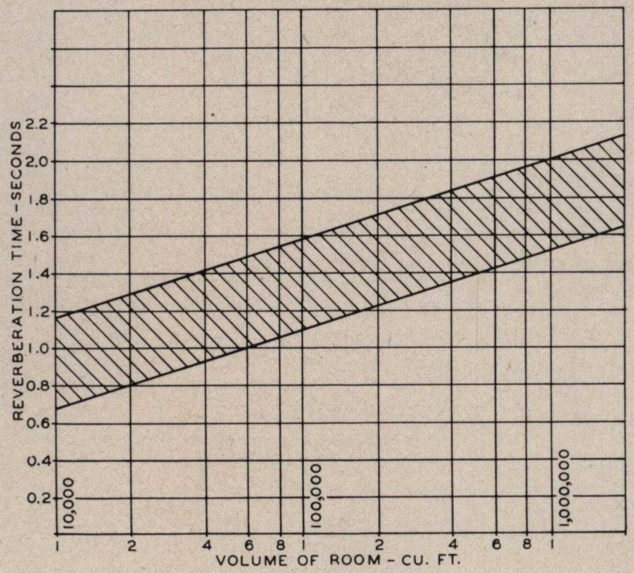

Fig. 14

factors in predetermining the planned reverberation. In Figure 14 the shaded area represents acceptable reverberation times for various room sizes, for the frequency 512 cycles per second. When treating sound film theaters or auditoriums which have a public address system, the reverberation times should fall nearer the lower limit of tolerance. In the case of churches and concert halls the times selected should fall nearer the upper limit of tolerance. The correction should be so computed that the desired reverberation time is obtained when occupied by an audience of the size that is usually present.

* The equivalent absorption of any portion of the interior surface of a room is the number of square feet of an ideal perfectly absorbing surface that would produce the same effect on the reverberation time as does the surface in question. Hereafter the simpler term "absorption" will be used with this meaning.

In computing the reverberation time of auditoriums the absorption coefficients at the single frequency 512 c. p. s. is used. In rating the effectiveness of absorbents in reducing room noise, it is common practice to use the average of the coefficients at 256, 512, 1024 and 2048 c. p. s. This average has been termed the NOISE REDUCTION COEFFICIENT.

7 COMPUTING REVERBERATION TIME—NUMERICAL EXAMPLE

A numerical example will serve to clarify the use of the Sabine formula in computing the reverberation time of an audience room of simple rectangular shape.

From the plans for the room and a table of absorption coefficients the necessary data are obtained and the following computations are made:

DIMENSIONS	VOLUME
112 x 56 x 28 ft.	175,000 cu. ft.

	DIMEN-SION	AREA	COEF.	ABSORP-TION
Floor, cement ...	56′ x 112′	6272 sq. ft.	.015	94 sabins
Walls, wood panelling	8′ x 336′	2688	.06	160
Walls, plaster on tile	20′ x 336′	6720	.025	168
Ceiling, plaster suspended	56′ x 112′	6272	.03	188
Velour curtain ..	39′ x 20′	780	.50	390

Total absorbing power, bare room...............1000 sabins
Plus 800 unupholstered seats @ .25 sabins....... 200 sabins

Assume that each seat when occupied has an absorption of 4.3 sabins. Then the presence of each member of the audience will increase the total absorption by $4.3 - .25 = 4.05$. We then compute the absorptions and the reverberation times under varying audience condition as shown below:

AUDIENCE	ABSORPTION	$\frac{.05V}{a}$
None	1200 sabins	7.3 seconds
200	2010	4.3
400	2820	3.1
600	3630	2.4
800	4440	2.0

From Figure 14, we note that the reverberation time even with a capacity audience is greater than is the maximum acceptable time for a room of this size. This means that because of excessive reverberation, it will be hard to understand speech in this room. The obvious remedy is to reduce the reverberation time by increasing the total absorption by the application of absorbent materials to the walls and/or ceiling.

ACOUSTICAL DEFECTS IN AUDITORIUMS

Rooms are rendered acoustically good through the absence of defects rather than by the possession of positive virtues. The chief sources of acoustical difficulties may be grouped under two heads; namely, ANNOYING ECHOES, and EXCESSIVE REVERBERATION.

1 ECHOES

Echoes of a short sharp sound, such as a single vigorous hand clap, may be observed in almost any large room. In a highly reverberant room, an echo, as a distinct repetition of the direct sound, will be lost in the general reverberation. In a heavily damped room, one with a short reverberation time, the echo from an extended unbroken surface is easily perceptible if the time interval between the arrival of the direct and reflected sound is more than 1/20 of a second. If sound is reflected from a plane or a convex curved surface, its intensity will be much lower than that of the unreflected sound and in general will be acoustically innocuous. If, however, the sound wave is reflected from a concave surface, the focusing action of the reflecting surface may produce a concentration of the reflected sound in certain areas, and result in annoying echoes and loss of intelligibility of speech.

A rear wall with a uniform curvature centering at a point on the stage is apt to produce an annoying echo in the forward portion of the room. Similarly, a high curved ceiling with center or axis of curvature near the seating level is a likely source of acoustical difficulty caused by focused ceiling echo. Acoustical defects of this sort are hard to correct once the building is completed, and should be avoided in the original design.

So-called "slap back" in talking motion picture theaters is a frequent source of acoustical difficulty. Here not only the rear walls, but the curved lines of seats contribute to a concentration of reflected sound in the forward portion of the theater. The most effective remedy lies in the proper directional pattern as well as in the placement of the loud speaker.

2 EXCESSIVE REVERBERATION

As has already been indicated, excessive reverberation is a common acoustical defect and one for which an adequate and practical remedy has been found in the use of commercial sound absorbents. The use of the reverberation formula in determining the amount of acoustical treatment needed in a particular case will be given in the next section.

3 HOW MUCH ACOUSTICAL TREATMENT?

Referring to the sample calculations of Section (2) it will be noted that the audience of 800 persons supplied almost three-fourths of the total absorption of the fully occupied room, and that the presence of the audience reduced the reverberation time from 7.3 seconds to 2.0 secs. The amount of added absorption that will be needed will thus depend upon the size of the audience that would normally be expected. Assume in this case that the usual audience will be 400 persons, and that the desired reverberation time with an audience of this size is 1.5 seconds. Then the total absorption after acoustical correction should be

$$a_{400} = \frac{.05V}{1.5} = \frac{.05 \times 175{,}000}{1.5} = 5830 \text{ sabins}$$

Referring to the value for an audience of 400 in the untreated room we find the necessary increase in absorption is

$$5830 - 2820 = 3010 \text{ sabins.}$$

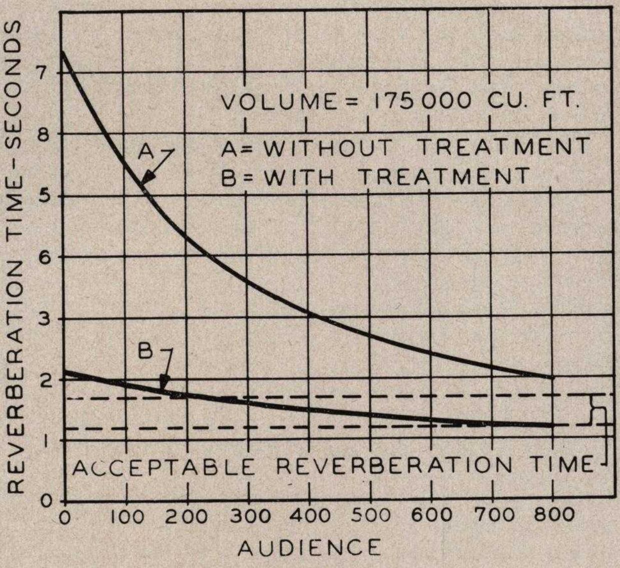

Fig. 15

In Fig. 15, the reverberation times in the treated and untreated rooms are plotted against the number of people in the audience. One notes that the reverberation time for the treated room falls within the acceptable range for all audiences greater than 200 persons.

4 AREA OF TREATMENT

The area of treatment will be found by dividing the necessary added absorption by the coefficient of the material to be used. The areas needed to give the added absorption of 3010 sabins, using coefficients of .40, .60 and .80, are as follows:

COEFFICIENT	AREA REQUIRED
.40	7525 sq. ft.
.60	5017 " "
.80	3762 " "

There may be cases where for architectural reasons the area available for treatment is limited. If in this case only 4500 feet on the ceiling were available for treatment, there would not be sufficient area for the .40 material or the .60 material. However, a correction could still be obtained for a certain range of audience sizes. The added absorption is .40 x 4500 = 1800 units and .60 x 4500 = 2700 and .80 x 4500 = 3600.

	REVERBERATION TIME		
AUDIENCE	.40 material	.60 material	.80 material
None	3.0 sec.	2.3 sec.	1.8 sec.
200	2.3	1.9	1.6
400	1.9	1.6	1.4
600	1.6	1.4	1.2
800	1.4	1.2	1.1

The .40 material gives satisfactory reverberation times from approximately two-thirds to capacity audience; the .60 material gives satisfactory results from approximately one-third capacity audience; and the .80 material gives results which can be considered satisfactory for any size audience, although the value with a full audience is a little below the acceptable reverberation range. In this connection it can be stated that values below the acceptable range are generally preferable to values above that range.

The above example shows that considerable latitude is available in the choice of the coefficient of a material. In general, this latitude is greater in rooms having a large amount of absorption in the form of upholstered seats, carpets, draperies, etc., than in rooms with less absorbent furnishings.

If the area of treatment can be varied, then the choice of coefficient to produce a given result is obviously wider.

5 LOCATION OF ABSORBING MATERIAL

The location of absorbing materials must depend upon circumstances to a certain extent. The use of highly absorbent materials on or near the stage is not good practice. Extended rear walls, especially when curved, should be highly absorbent. Normally, ceiling areas will be found the most feasible for the installation of acoustical treatment. Treatment applied on under-balcony ceilings is undesirable and is less effective in reducing general reverberation than equal areas applied to ceilings or side walls of the main portion of an auditorium. In wide rooms with low ceilings, side wall treatment, when practicable, is preferable to ceiling treatment. Choice of materials for any case should be made on the basis of adaptability to the particular demands of the situation rather than on a few points of difference in the absorption coefficients.

6 REVERBERATION AT DIFFERENT FREQUENCIES

Since the absorption coefficients of materials are different at different frequencies, it follows that the reverberation time of a given room will depend upon the pitch of the sound, and that, theoretically at least, the variation with frequency of the absorption coefficient of any material will have an effect upon the acoustic properties of a room in which it is used. It is a common practice to consider the reverberation only at the single frequency of 512 cycles per second. No very definite criterion for reverberation times at other than 512 cycles has been established, but experience shows that in an auditorium with a large area of material having a coefficient at high frequencies several times as great as that at 128 cycles, a preponderance of low pitched sound results which is not pleasing. The importance of considering the coefficients at different frequencies is apparent, in cases such as broadcasting studios in which the artificial absorbent supplies most of the total absorption. In rooms where only a small portion of the total absorption is supplied by the acoustical material, this factor may be unimportant. This is the case in auditoriums generally. Here the absorption of the audience furnishes so large a part of the total absorption that the effect of the introduction of acoustical treatment on the reverberation frequency characteristic is negligible. In the usual case, adjustment of the latter is a refinement of quite secondary importance as compared with securing the proper reverberation time as computed from absorption coefficients at 512 c. p. s.

7 EXTRANEOUS NOISE

Disturbing sounds even at low intensity levels may seriously lower the intelligibility of speech in an auditorium. This is particularly true in cases where the intensity level of the desired sound is comparatively low. Outside traffic noise, noise from machinery outside the room, such as ventilating fans, circulating pumps, electric motors and the like, frequently cause complaints on the score of poor acoustics regarding rooms that are otherwise acoustically good. Traffic noise can be fairly well eliminated by an acoustically treated lobby between the auditorium proper and the street. Heavy machinery should preferably not be mounted on structural members that are tied in directly with the walls, floor or ceiling of the auditorium, and in any case should be mounted on properly designed resilient mounts. Ventilating air should be admitted and vented at low velocity through grilles designed to reduce grille noise and ventilating ducts should be lined for a distance of at least 16 feet from the vent openings with highly absorbent material. Projection booths in motion picture theaters should be acoustically treated and have walls with good sound insulating properties.

8 ACOUSTICS IN AUDITORIUM DESIGN

Good acoustical design consists largely in avoiding sources of acoustical defects. A few general rules to this end can be set down which will be useful in the layout of the rough plans for a proposed auditorium. However, there are many points on which experience alone can give proper guidance, so that it is strongly urged that in the design of rooms in which excellent acoustic properties are of prime consideration the services of a competent acoustical consultant be secured. What has been suggested in the sections dealing with acoustical defects may be summarized as follows:

1. Contours of side walls and ceiling in the front of the room should reflect sound at nearly glancing

angles to the sides and rear of the room. This calls for walls splayed from the stage opening and a ceiling sloping upward from the stage opening.

2. Extended concave wall or ceiling surfaces, particularly those having curvatures in two planes, should not have centers or axes of curvature that fall either on the stage or near any portion of the audience. These almost sure-fire causes of acoustical difficulty should be avoided in the design of an auditorium.

3. Average ceiling heights should be determined from the number of seats, so that the volume of the room in cubic feet is not greater than 200 times the number of seats.

4. The total absorption should be such that with the average audience present, the reverberation time as computed by the Sabine formula falls within the range of acceptable values for a room of the proposed volume as given in Fig. 14.

5. The required absorbing material should generally be placed on those areas which might produce interfering delayed reflections of sound, such as high ceilings, rear walls, and widely separated side walls, rather than on surfaces furnishing useful reinforcing reflections, such as low ceilings and stage and proscenium surfaces.

6. Sound amplification will not be of much use in a too reverberant room. In very large rooms in which the reverberation has been properly controlled, a public address system is desirable to insure sound levels at which speech is easily intelligible. The placement and directional pattern of the loud speaker should be such that the main beam of amplified sound is not reflected from an extended non-absorbent surface directly back to the microphone. Heavily damped rear walls with the loud speaker placed so that the main beam is directed to the seating area will reduce the possibility of acoustical feed-back that is sometimes encountered with public address systems.

SOUND CONDITIONING IN WORK ROOMS

The earlier uses of sound absorbents were largely confined to the control of acoustics in auditoriums. A much more extensive use today is in their application to the reduction of noise levels in rooms where quiet conditions have been shown to be a definite commercial asset in the increased comfort and efficiency of workers.

Sound produced in the open air, away from any reflecting surface, travels from the source to the listener, is heard once and that is the end of it. In such a case, moreover, the intensity decreases with increasing distance from the source. In a room, however, repeated reflections prolong each sound, thus building up a general sound level, much greater than would result from the same source without reflection. It can be shown that with a given amount of noise generated in a room, the average intensity of the reflected sound varies inversely as the total absorption of the room, i. e., doubling the absorption halves the physical sound intensity. The reduction in the intensity of the reflected sound is, however, only one of a number of factors which contribute to the overall effect of quieting by the use of acoustical absorbents on walls and ceiling of noisy work spaces. Its value lies in the reduction of the "annoyance factors" of noise more than in changes in physical factors which can be measured.

1 OFFICE QUIETING

The modern business practice of congregating a large number of workers and business machines within a single room results in a noise condition that has been shown by actual measurement to increase fatigue and lower the efficiency of office workers. The character of the noise in such an office without acoustical treatment is peculiarly distracting, for the following reasons:

(a) Reverberation from untreated walls and ceilings lowers the intelligibility of speech even at short distances.

(b) Due to reflection from non-absorbent wall and ceiling surfaces, the noise from distant sources is almost as loud as that from sources near at hand.

(c) Telephone conversation is difficult due to the masking effect of the room noise.

(d) Due to the noise and loss of intelligibility persons speaking will raise their voices above the normal level, thus increasing the general noise throughout the room.

(e) The actual physical intensity level in decibels of the reverberant sound is greater than it would be from the same sources of noise in the same room, but with absorbent treatment.

2 NUMERICAL EXAMPLE OF OFFICE QUIETING

Take as an example a typical office 40 x 50 ft. with a 10-foot ceiling. The volume is 20,000 cu. ft. The total absorption with the usual office equipment and twenty occupants would be roughly 300 sabins. Suppose now that 1800 sq. ft. of absorbent material with a noise reduction coefficient of .70 is applied to the ceiling. The total absorption is now 300 + (1800 x .70) = 1560 sabins, which is equivalent to 5.2 times the absorption of the untreated room. The reverberation is reduced by this factor from 6.6 to 1.3 seconds. It can be shown that the reductions in the intensity of that portion of the noise that is due to reverberation is reduced in the same ratio, namely, 5.2. From Figure 5 this reduction corresponds to a drop of 7.2 decibels in the intensity level. If the initial noise level was that of a noisy office, say 70 db., then from the 70 db. curve of Figure 9 we get a reduction of 35 percent in the loudness of the noise. Experience in numberless cases has shown that 35 percent is a very conservative figure for the increase in the comfort and efficiency with which the work of such an office is carried on.

It is impossible to assess numerically the various elements of increased working comfort, or to lay down definite rules for the amount of added absorption required to give a desired result. Experience has shown that increasing the total absorption by a factor as small as three produces a marked quieting effect. Speaking generally, the use of absorbent treatment for quieting is not apt to be overdone. In ordinary office rooms with ceilings not more than 12 feet in height, covering the ceiling alone with a material whose NOISE REDUCTION COEFFICIENT is .60 or more will meet the requirements. In small private offices with limited ceiling areas additional treatment on walls has been found to be essential to secure the degree of quieting desired.

In loftier rooms, such as the public space in banks, wall treatment as well as ceiling treatment is desirable. In such cases, however, the surfaces that are available will probably be the limiting factor.

3 QUIETING OF INDUSTRIAL PLANTS

The principles involved in the reduction of noise in manufacturing plants are the same as for office quieting. However, the noise levels are considerably higher than those ordinarily encountered in offices, and conditions as to ceiling height, grouping of machines and the character of the noises to be controlled make it difficult to generalize.

During the war a considerable number of plants were built in which extensive acoustical treatment was installed. Noise level measurements made in some of these showed that, while factory conditions are such that the actual reduction in the noise level was, in general, less than would be expected on the simple reverberation theory, yet the workers reported that the treated areas "seemed less noisy". The explanation would appear to lie in the fact that while the directly transmitted noise originating in the workers' immediate vicinity is not reduced, yet the effect of acoustical treatment on reverberation and noise from distant sources appreciably reduces the "noisiness" of the general environment. En-

lightened industrial management is coming more and more to recognize that in new plant construction acoustical treatment is worth the small increase in construction costs.

4 OTHER QUIETING APPLICATION

Only a few of the many uses to which sound absorbents are now being put for quieting purposes can be mentioned.

HOSPITALS. Until rather recent years sound absorbent treatment in hospitals was banned on the score of sanitation. Experimental studies have shown, however, that this objection is groundless in the case of modern acoustical materials in which surface renewals are possible by painting or otherwise. Ceiling treatment of corridors, diet kitchens, service rooms, nurseries and delivery rooms is now accepted as a desirable measure for reducing noise and improving conditions conducive to the recovery of patients in modern hospitals.

RESTAURANTS. In restaurants with uncarpeted floors, plaster or tile walls and ceilings, hard table tops without cloths, the noise of trays, rattling dishes and silverware produces anything but comfortable conditions for eating. Restaurant managers have found that quiet surroundings constitute a definite commercial asset for their establishments.

SCHOOLS. The fireproof construction of modern school buildings tends to make them extremely noisy places due to the highly sound-reflecting properties of their interior surfaces. There is scarcely any part of a modern school in which sound absorbent treatment is not desirable, or even essential. Corridors, stair halls, band or orchestra rehearsal rooms, typing classrooms, cafeterias and ordinary classrooms are all places where the normal noise-making propensities of youngsters are enhanced by the lack of sound absorption of fireproof construction. Here also sound absorbent treatment of ceilings is the obvious remedy. The school gymnasium, with its higher ceiling and long reverberation time, should have enough added absorption to reduce the empty room reverberation to a matter of 2.0 or 2.5 seconds, both for quieting and to facilitate class instruction.

5 MISCELLANEOUS NOISE PROBLEMS

Aside from the foregoing, mention may be made of libraries, waiting rooms in railroad stations and airports, ballrooms, skating rinks, and bowling alleys as locations where the reduction of noise levels obtainable by the use of acoustical absorbents is desirable.

6 MEASUREMENT OF SOUND ABSORPTION COEFFICIENTS

There are a number of different ways in which the sound absorption coefficients of materials may be measured. The reverberation method is the one most commonly used. The method is essentially as follows:

The Reverberation Time of a fairly large empty room, with highly-reflecting walls, floor and ceiling (called a Reverberation Chamber) is determined by measuring the times required for reverberant sounds of different initial intensity levels to decrease to a fixed level. The relative values of the initial levels are given by the measured levels of the electrical power input to the loud speaker which generates the sound. The initial levels are

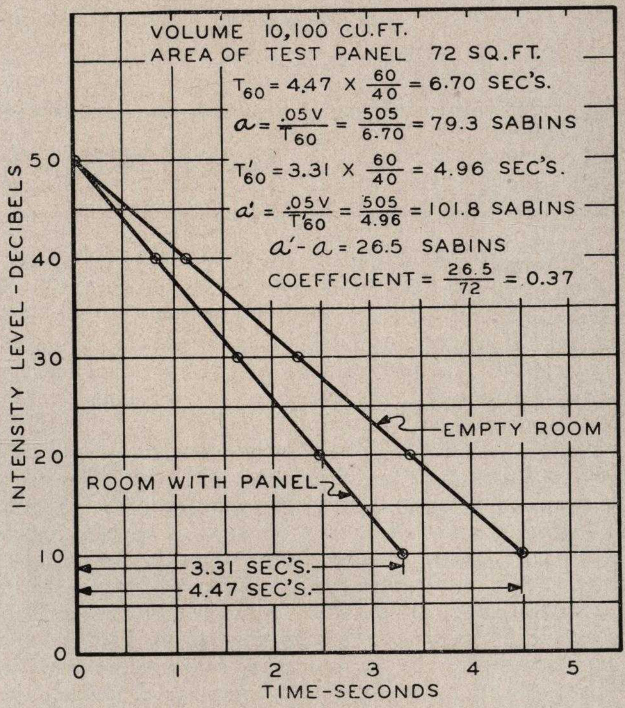

Fig. 16

plotted against the average value of a large number of observed times for each initial level, and give a straight line as shown in Figure 16. From the slope of this line the time for a 60 db. drop in intensity level can be computed. This is the T of the Sabine formula, which can now be used to compute a, the absorption of the empty Reverberation Chamber. A standard area of the material to be measured, mounted as it would be in actual practical application, is then brought into the room. The measurements that were made in the empty room are repeated, and the absorption a', of the room and sample, computed. The difference is the added absorption due to the test sample. This, divided by the area, gives the increase of absorption per unit area. Adding to this the absorption coefficient of the room surface covered by the sample, we have the absorption coefficient of the tested material.

Measurements are made and reported in the Bulletins of the Acoustical Materials Association at the frequencies of 128, 256, 512, 1024, 2048 and 4096 cycles per second.

7 COEFFICIENTS TO BE USED FOR DIFFERENT PURPOSES

For AUDITORIUM CORRECTION it has been customary to use the single coefficient at 512 cycles alone. Since the absorption of a material may vary widely with frequency, it is important in some cases to give consid-

eration to the coefficients at frequencies other than this. Particularly is this true in the case of sound recording and broadcasting studios where the reverberation frequency characteristics are very largely determined by the coefficients of the artificial absorbent used.

For QUIETING, the average, taken to the nearest multiple of .05, of the coefficients at 256, 512, 1024, and 2048 cycles is recommended and is used as a basis for comparison of materials. This average is called the noise reduction coefficient. Strictly speaking, this average has no physical meaning, and has been adopted by the Acoustical Materials Association only as a means of roughly assessing the relative merits of acoustical materials when used for quieting purposes.

Section 5

SOUND INSULATION

The terms sound insulation and sound absorption are often confused. The former applies to the reduction of sound intensity when transmitted from room to room by way of intervening walls, floors or ceilings. The latter refers to that portion of the sound incident upon a surface that is not reflected from it. Mechanically, the two phenomena are quite different. The sound insulating value of a porous highly sound absorbent material will be relatively small in comparison with that of a solid impervious partition. Measurements have shown that 4 inches of hair felt closing an opening gives a much smaller reduction of sound intensity on the further side than does a solid wall of plaster only 1½ inches thick.

Transmission of sound by way of a solid partition occurs as a result of the vibration set up in it by the alternating pressure of the sound waves on its surface. These vibrations set up sound waves much reduced in intensity in the space on the opposite side. Strictly speaking, there is no transmission of sound as sound THROUGH the wall. The problem of sound insulation thus becomes a matter of reducing the diaphragmatic vibration of the wall under the alternating pressure of the sound incident upon its face, rather than of absorbing sound energy within the body of the walls. It is for this reason that the common practice of putting sound absorbing material inside hollow constructions, such as a wood stud and plaster partition, usually gives disappointing results.

1 TWO TYPES OF SOUND INSULATION PROBLEMS

It is important to distinguish between the case in which sound insulation is desired between adjoining rooms with an intervening wall, and that of reducing the sound produced by mechanical impacts, such as foot falls on a floor and ceiling construction or by vibrations of a machine in rigid connection with structural members. The first is spoken of as insulation against AIR-BORNE SOUND, and the second as insulation against IMPACT SOUND. The methods used in the two cases are quite different.

2 SOUND INSULATING METHODS

Extensive laboratory studies have shown that the sound insulating efficiency for AIR-BORNE SOUND of single walls of solid masonry, and of single stud or joist construction is largely dependent upon their weight per unit area. In constructions of this type, high insulating efficiency can be obtained only by great weight.

High efficiency without excessive weight can be obtained by the use of double-wall constructions in which there is a high degree of structural isolation between the component members. Structural bridging will materially decrease the effectiveness of a double-wall construction. A narrow air space, less than 2 inches say, gives considerable coupling between the two members. A fairly heavy wall faced with a much lighter screen wall isolated from it by means of properly designed vibration isolators has been shown to give a higher degree of insulation than a solid wall of the same weight. What has been said of walls applies also to floors in the case of air-borne sounds, such as the sounds of voices or of musical instruments which are not in solid contact with the floor.

The insulation against sound produced by impact of solid objects on floors is most effectively accomplished by reducing the noise of the impact. A solid concrete slab, which is fairly effective in reducing air-borne sound, transmits impact sound to a surprising degree. High efficiency against impact sound is principally a matter of absorbing the energy of the impact before it can get into the floor structure. Covering the floor with felt-lined carpeting helps materially. Another more elaborate means is to provide floating floor construction carried on resilient mounts. Provision of a suspended ceiling in the room below with a considerable air space between the floor slab and ceiling has been found to give good insulation against impact sounds on concrete floors.

The elimination of sound due to the vibration of a machine mounted on a floor or ceiling can only be effected by means of properly designed vibration isolators. There are various types of these devices now on the market. Their effectiveness depends upon reducing the natural frequency of the machine on its resilient mount to a point well below the frequency of the vibrations which its moving parts produce. This is an engineering rather than an acoustical problem, and each case calls for individual solution.

3 SOUND TRANSMISSION LOSS

The sound insulating efficiency of walls or other structural units for air-borne sound is given by what is known as the Transmission Loss for that particular construction. Transmission Loss is expressed in decibels. It is measured by measuring the difference in intensity levels between two rooms, in one of which the sound originates and from which it is transmitted to the other room by way of the wall or other structural unit sepa-

rating the two, and making the proper corrections for the area of the transmitting surface and the total absorption of the room in which the transmitted sound is received. Transmission Loss measurements are made under certain specified conditions as to all the factors that affect the difference of intensity levels between the transmitting and receiving rooms.

4 TRANSMISSION LOSSES OF SOME TYPICAL CONSTRUCTIONS

The figures of the following table will give an idea of the Transmission Loss of various types of partitions in ordinary building construction. The values given are the averages of measurements at 25 frequencies, covering the range from 125 to 2070 cycles per second.

CONSTRUCTION	WT./SQ. FT.	TRANSMISSION LOSS
1. Solid masonry of gypsum and clay tile, plaster and brick	10 to 88 lbs.	26 to 54 db.
2. Haydite, cinder and slag concrete block, plastered	23 to 56 lbs.	43 to 53 db.
3. Lead, glass and steel sheets	1 to 10 lbs.	25 to 40 db.
4. 2 x 4 inch wood stud, metal lath and gypsum plaster	17.4 lbs.	34 db.
5. The same with lime plaster	17.4 lbs.	43 db.
6. Wood doors of various types of usual construction	—	22-30 db.
7. 6 inch wall, 2 x 4 inch staggered studs, metal lath and gypsum plaster	20 lbs.	45 db.

5 OVER-ALL SOUND INSULATION

In cases where two adjoining rooms are separated by a dividing structure composed of elements showing different values of the Transmission Loss, the over-all sound insulation is NOT the average of the transmission losses of the separate elements estimated in proportion to their respective areas. This is due to the fact that the decibel is a logarithmic unit and the average of the logarithms is not the logarithm of the average. For this reason an element showing a low transmission loss will have a disproportionate effect on the over-all sound insulation. For example, the proper computation of the over-all insulation of 150 square feet of 40 db. wall, with a 3 x 7 foot door showing a 22 db. loss, gives an over-all reduction of only 28 db. In fact, any job of sound insulation is not apt to be much better than the least efficient element in it. Hence, appears the importance of providing doors and windows with transmission losses that approximate those of the wall structure itself, and also of sealing effectively threshold and clearance cracks around door and window openings.

Double walls of solid masonry, with a minimum of structural bridging and an ample intervening air space, are the most effective means of securing a high degree of sound insulation without excessive weight. Filling the inter-wall space with sound absorbent material does not add materially to the sound insulating value of this type of construction.

Partitions of cinder or slag cement block should be plastered on one side at least to reduce direct transmission of sound through the porous body of such materials. The insulation of existing clay or gypsum tile partitions may be materially increased by adding a furred lath and plaster screen wall with strips of ½ inch felt inserted between the furring strips and the tile. Fiber board applied directly to an existing wall does not materially increase the degree of sound insulation.

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